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FOR

INTERFEROMETERS UTILIZING POLARIZATION PRESERVING OPTICAL SYSTEMS

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Title: **INTERFEROMETERS UTILIZING POLARIZATION PRESERVING OPTICAL SYSTEMS**

CROSS REFERENCE TO RELATED APPLICATION

This application is related to commonly owned, copending United States Patent Application No. 09/384,742 ~~(Attorney Docket No. 0200/US)~~ filed on even date herewith in the name of Henry Allen Hill and entitled POLARIZATION PRESERVING OPTICAL SYSTEMS.

BACKGROUND OF THE INVENTION

This invention in general relates to displacement measurement interferometry and more particularly to displacement measurement interferometers (DMIs) that utilize polarization preserving optical systems to enhance their accuracy by reducing undesirable polarization effects.

In polarization interferometers for the measurement of linear and angular displacements, one or more orthogonally polarized beams are introduced into the interferometer and then are separated by a polarizing beam splitter for travel along reference and measurement legs. Afterwards, the beams are recombined and information about the difference in the optical path lengths they traveled is analyzed to yield displacement. In the process of traveling through the interferometer, perhaps making multiple passes, the polarized beams typically encounter retroreflectors that return them from either fixed or moveable mirrors. Such retroreflectors, which are non-polarization preserving, introduce errors in the accuracy of the measurements obtainable because they do not

2

preserve the state of polarization of the beams to a degree consistent with the demands for high accuracy.

Such non-polarization preserving retroreflectors are well-known and operate to deflect light through 180 degrees such that an incoming beam is exactly reversed in direction, traveling as an outgoing beam parallel to the direction of propagation of the incoming direction and spatially offset with respect to it. The classical retroreflector essentially contains the intersection corner of three mutually perpendicular plane surfaces and is known as the cube corner retroreflector or sometimes the tetrahedron. Here, a ray generally undergoes 3 reflections, one from each 120° sector in the process of entering and exiting the retroreflector. Ideally, the direction of the reflected ray is opposite that of the incident ray but displaced due to a reflection through the retroreflector intersection corner. From the standpoint of polarization effects, the primary problem with the classical retroreflector is that the angles the rays make with the mirror surfaces are skew. Detailed calculations using the Jones matrix formalism, along with the Fresnel reflection formulas, can be used to predict the resultant polarization for different initial polarizations and retroreflector types. From the standpoint of their use in DMI applications where small, linearly polarized beams interact with only small sub-apertures of the retroreflector, the net effect is to rotate the plane of polarization by several degrees (typically 6°). This phenomenon is called Retro Induced Polarization Rotation (RIPR) and misaligns the beam polarization directions with respect to the polarization beam splitter of the

interferometer which can cause large periodic errors in the measured interferometric phase. A particularly troublesome periodic or "cyclic" error which occurs in High Stability Plane Mirror Interferometers (HSPMI) produces an error with a frequency at ½ the Doppler shift (as well as other frequencies). It has been shown that this error, which is due to the polarization rotation properties of the retroreflector, can be extremely large and will occur regardless of the beamsplitter quality.

Consequently, it is a primary object of the present invention to provide polarization interferometers utilizing polarization preserving optical systems that provide beam deflection properties without introducing deleterious polarization effects.

It is another object of the present invention to provide displacement measurement interferometers that use polarization preserving optical systems in place of traditional cube corner retroreflectors.

Yet another object of the invention to provide polarization plane mirror interferometers that utilize polarization preserving optical systems to enhance displacement measurement accuracy.

It is still another object of the present invention to provide polarization plane mirror interferometers that utilize internally tilted surfaces for purposes of reducing the effects of undesirable ghost beams on accuracy.

It is yet another object of the present invention to provide polarization plane mirror interferometers that utilize retardation elements in one or more interferometer legs to reduce the effects of ghost images.

Yet another object of the present invention is to provide polarization preserving optical systems for use at multiple wavelengths.

It is yet another object of the present invention to provide multiple-pass (two or more) polarization plane mirror interferometers that utilize polarization preserving optical systems.

e Other objects of the invention will, in part, be obvious and will, in part, appear hereinafter when the following detailed description is read in connection with the accompanying drawings.

SUMMARY OF THE INVENTION

The present invention relates to polarization interferometric apparatus that utilize polarization preserving optical systems to deviate plane polarized beams through preselected angles without changing their linear state of polarization. The inventive polarization interferometric apparatus have a variety of applications and are particularly suitable for use in distance measuring interferometry (DMI) to achieve higher measurement accuracy than is otherwise possible. This is achieved by reducing undesirable polarization effects that can introduce errors associated with an otherwise present undesirable polarization rotation found in classical retroreflectors. Such interferometers find additional utility in the fabrication of integrated circuits via microlithographic techniques.

While a number of embodiments of the polarization interferometric apparatus of the invention are described, they all share in common the use of interferometer means

for receiving at least two beams having orthogonal states of polarization and providing first and second interferometer legs, separating the two beams for travel along the first and second interferometer legs, respectively, and generating exit beams containing information about the respective differences in the optical paths each beam experienced in traveling the first and second interferometer legs. The first and second interferometer legs have optical paths structured and arranged such that at least one of them has a variable physical length, and the optical path length difference between the first and second interferometer legs varies in accordance with the difference between the respective physical lengths of their optical paths and wherein at least one of the first and second interferometer legs comprises a polarization preserving optical system.

The polarization preserving optical systems used in the polarization interferometric apparatus of the invention comprise a plurality of reflecting surfaces arranged such that a change in the direction of propagation of an input beam, normal to both the input beam and an output beam, causes a change in the direction of propagation of the output beam in a direction opposite to the direction of the change in the input beam, and a change in the direction of propagation of the input beam, normal to the input beam and in a plane orthogonal to a normal to both the input beam and the output beam, causes a rotation in the output beam in the plane that is the same as a corresponding rotation of the input beam caused by the change in the direction of propagation of the input beam and wherein the plane of incidence at each of the

reflecting surfaces is either orthogonal or parallel to the plane of polarization of an incident beam thereto.

The polarization preserving optical systems are preferably fabricated of a plurality of prismatic optical elements wherein the plurality of reflecting surfaces comprise selected surfaces of the prismatic optical element and preferably operate by total internal reflection.

The plurality of prismatic optical elements are preferably arranged as an integral assembly in which at least one surface of each prismatic optical element contacts at least one surface of another prismatic optical element and in which at least one polarizing beam splitter may be included.

The prismatic optical elements are selected from the group consisting of Porro, right angle, Dove, penta, and "K" prisms, one embodiment comprises a sequential combination of a right angle prism, a Porro prism, and a pentaprism.

At least one of the plurality of reflecting surfaces may have formed thereon a multilayer polarizing beam splitter coating arrangement to enhance the extinction ratio between orthogonally polarized beams entering the polarization preserving optical system and originating upstream of it, and such coatings may be structured to operate at multiple wavelengths. Birefringent materials may also be used to construct the various prismatic optical elements for similar purposes.

A variety of input to output beam relationships is demonstrated and depend on the particular design geometry of a system.

Examples of polarization interferometric apparatus in which polarization preserving optical systems are used include, but are not limited to, plane mirror, high stability plane mirror, differential plane mirror, column, and dual linear/angular interferometers.

Means are also provided for generating at least two input beams that are orthogonally polarized, may be coextensive and overlapping or be spatially separated, and may operate at more than one wavelength, which may or may not be harmonically related.

Also included are means for combining the exit beams to produce mixed optical signals containing information corresponding to the phase differences between each of the exit beams from corresponding ones of the predetermined optical paths of the first and second interferometer legs.

Further included are means for detecting the mixed optical signals and generating electrical interference signals containing information corresponding to the difference in physical path lengths of the interferometer legs and their relative rate of change, and electronic means for analyzing the electrical interference signals.

At least one of the interferometer legs preferably includes retardation elements for controlling the state of polarization of orthogonally polarized beams and reducing the effects of ghost reflections on exit beams.

The interferometer means, which typically include a plurality of opposing surfaces, preferably have at least some of them tilted with respect to others to reduce the effects of ghost beams on exit beams.

BRIEF DESCRIPTION OF THE DRAWINGS

The structure, operation, and methodology of the invention, together with other objects and advantages thereof, may best be understood by reading the detailed description in connection with the drawings in which each part has an assigned numeral that identifies it wherever it appears in the various drawings and wherein:

Fig. 1a is a diagrammatic perspective view showing the relationship between beams entering and exiting an optical system having generalized polarization preserving optical system properties;

Fig. 1b is a diagrammatic perspective view showing the relationship between the input and output beams shown in **Fig. 1a** and a vector normal to both;

Fig. 1c is a diagrammatic perspective view showing the relationship between the input beam of **Fig. 1a**, the normal vector of **Fig. 1b**, and a vector normal to both;

Fig. 1d is a diagrammatic perspective view showing the relationship between the output beam of **Fig. 1a**, the normal vector of Fig. 1b, and a vector normal to both;

Fig. 2 is a diagrammatic perspective view showing the relationship between beams entering and exiting the optical system of **Fig. 1a** after a change in the direction of the input beam compared with its direction in **Fig. 1a**, the change being parallel to the normal of **Fig. 1b**;

Fig. 3 is a diagrammatic perspective view showing the relationship between beams entering and exiting the optical system of **Fig. 1a** after a change in the direction of the input beam compared with its direction in **Fig. 1a**, the change being in a plane that is perpendicular to the normal of **Fig. 1b** and the input beam of **Fig. 1a**;

Fig. 4 is a diagrammatic perspective view of a polarization preserving generalized optical system assembly comprising a Porro prism in combination with a right angle prism along with the relationship between input and output beams as they undergo changes in the direction in which the input beam enters the face of the Porro prism, the input and output beams being offset and perpendicular to one another;

Fig. 5 is a diagrammatic perspective view of a polarization preserving generalized optical system assembly comprising a Porro prism in combination with a Dove prism along with the relationship between input and output beams as they undergo changes in the direction in which the input beam enters the face of the Porro prism, the input and output beams being offset and at other than a right angle with respect to one another;

Fig. 6 is a diagrammatic perspective view of a polarization preserving generalized optical system assembly comprising a Porro prism in combination with a "K" type prism along with the relationship between input and output beams as they undergo changes in the direction in which the input beam enters the face of the Porro prism, the input and output beams being offset and parallel to one anther;

Fig. 7 is a diagrammatic perspective view of a polarization preserving generalized optical system assembly comprising a Porro prism in combination with a right prism and a penta prism along with the relationship between input and output beams and also shows the individual components of the assembly in exploded fashion,

the input and output beams being parallel and offset with respect to one another;

Fig. 8 is a diagrammatic perspective view of a polarization preserving optical system assembly comprising a polarizing beam splitter with a roof prism, and a Porro prism in combination with two angle right prisms along with the relationship between two input and two output beams of the assembly, the input and output beams being offset, parallel, and all lying in a line;

Fig. 9 is a diagrammatic perspective view of a plane mirror interferometer employing two polarization preserving optical system assemblies of the type shown in **Fig. 7**;

Fig. 10 is a diagrammatic perspective view of a high stability plane mirror interferometer employing a single polarization preserving optical system assembly of the type shown in **Fig. 7**;

Fig. 10a is a diagrammatic perspective view of a high stability plane mirror interferometer employing a single polarization preserving optical system assembly of the type shown in **Fig. 7** along with a prismatic optical element for providing a four-pass arrangement to enhance sensitivity;

Fig. 11 is a diagrammatic perspective view of a high stability plane mirror interferometer employing a single polarization preserving optical system assembly of the type shown in **Fig. 7** along with a split quarter-wave plate in the intervening space between its polarizing beam splitter and the object mirror, the plates of the split quarter-wave plate being tilted relative to each other to prevent unwanted polarizing mixing;

Fig. 12 is a diagrammatic perspective view of a differential plane mirror interferometer employing a single polarization preserving optical system assembly of the type shown in **Fig. 7** along with a shear plate with polarizing beam splitter surfaces to spatially separate and combine input and output beams;

Fig. 13 is a diagrammatic elevational view of the assembly of **Fig. 12** illustrating various paths of travel of beams as they propagate through the assembly; and

Fig. 14 is a diagrammatic perspective view of a high stability plane mirror column type interferometer employing a single polarization preserving optical system assembly of the type shown in **Fig.** 7 along with a split quarter-wave plate in the intervening space between its polarizing beam splitter and the object mirror, the plates of the split quarter-wave plate being tilted relative to each other to prevent unwanted polarizing mixing;

Fig. 15 is a diagrammatic plan view of a dual high stability interferometer employing a pair of polarization preserving optical system assemblies for measuring linear and angular displacement;

Fig. 16a is a diagrammatic perspective of a differential plane mirror interferometer employing polarization preserving optical systems along with a dynamic element for assuring that a measurement beam thereof remains aligned perpendicular to its plane object mirror ;

Figs. 16b through **16e** are plane view of various elements of the interferometer of **Fig. 16a**;

Fig. 17 is a diagrammatic perspective of a polarization preserving optical system assemblies shown in

12

combination with a polarizing beam splitter, one of the prismatic elements of the optical system assemblies having reflecting surfaces with multilayer beam splitter arrangements formed thereon to enhance the extinction ratio of the combination;

Fig. 18 is a diagrammatic elevational view of a penta prism formed of a birefringent element illustrating its ability of receiving an incoming beam having two coextensive orthogonally polarized components and separating it into two outgoing orthogonally polarized beams that have different directions of propagation and are spatially separate;

FIG. 19a-19c relate to lithography and its application to manufacturing integrated circuits wherein **FIG. 19a** is a schematic drawing of a lithography exposure system employing the interferometry system.

FIGS. 19b and **19c** are flow charts describing steps in manufacturing integrated circuits; and

FIG. 20 is a schematic of a beam writing system employing the interferometry system.

DETAILED DESCRIPTION OF THE INVENTION

The present invention relates to polarization preserving optical systems and their use as components in displacement measuring interferometers. Accordingly, the structure and properties of the polarization preserving optical systems per se will first be described and then their application in displacement measuring interferometers will be taken up.

Various embodiments of the polarization preserving optical systems of the invention will be described, and

each polarization preserving optical system comprises two properties. The first property that such optical systems possess is a set of orientations of planes of linear polarization for which the polarization state of an input beam at each reflecting and refracting surface of the optical system and a corresponding output beam are all linear. The set of planes of linear polarization orientations hereinafter will be referred to as eigenmodes. Thus, the optical systems "preserve", for an input beam to the system having an eigenmode state of linear polarization, the linear states of polarization of the input beam at each reflecting and refracting surface of the optical system and the corresponding output beam.

A set of the optical systems that exhibit such eigenmodes comprise reflecting and refracting surfaces such that the plane of polarization of an eigenmode at each of any reflecting or refracting surface in the optical system is either parallel to or orthogonal to the plane of incidence at the surface.

The second property that apparatus of the various embodiments described herein further possess is a certain set of transformation properties. The set of transformation properties describe a specific relationship between changes in the direction of propagation of an output beam from an optical system that results from changes in the direction of propagation an input beam where the directions of propagation of the input and output beams may or may not be parallel. This set of transformation properties will hereinafter be referred to as a transformation type T_{Ret}.

FIG. **1a** is a diagrammatic perspective view showing the relationship between vectors $\vec{k}_1$ and $\vec{k}_2$ representing the directions of propagation of optical beams entering and exiting, respectively, an optical system exhibiting transformation properties of the transformation type T_{Ret}. The magnitudes of input and output vectors, $|\vec{k}_1|$ and $|\vec{k}_2|$, respectively, are equal to respective wavenumbers $k_i = 2\pi/\lambda_i$ for $i=1$ and 2 where λ_i is the wavelength of a respective vector.

The transformation properties of the transformation type T_{Ret} are defined in terms of infinitesimal changes $\Delta\vec{k}_1$ and corresponding infinitesimal changes $\Delta\vec{k}_2$ in vectors $\vec{k}_1$ and $\vec{k}_2$, respectively, to form vectors $\vec{k}_1'$ and $\vec{k}_2'$, respectively, wherein infinitesimal changes $\Delta\vec{k}_1$ and $\Delta\vec{k}_2$ are orthogonal to vectors $\vec{k}_1$ and $\vec{k}_2$, respectively, $|\vec{k}_1'| = |\vec{k}_1|$, and $|\vec{k}_2'| = |\vec{k}_2|$. Thus, the infinitesimal changes $\Delta\vec{k}_1$ and $\Delta\vec{k}_2$ produce rotations of $\vec{k}_1$ and $\vec{k}_2$, respectively, about axes orthogonal to $\vec{k}_1$ and $\vec{k}_2$, respectively.

An arbitrary infinitesimal change $\Delta\vec{k}_1$ can be represented as the sum of two orthogonal infinitesimal vector components $\Delta\vec{k}_{1\|}$ and $\Delta\vec{k}_{1\perp}$. Component $\Delta\vec{k}_{1\|}$ is defined as a component parallel to a unit vector $\hat{a}$. Unit vector $\hat{a}$ is defined as a vector cross product, $\vec{k}_1 \times \vec{k}_2$, of $\vec{k}_1$ and $\vec{k}_2$ normalized by the magnitude, $|\vec{k}_1 \times \vec{k}_2|$, of $\vec{k}_1 \times \vec{k}_2$, *i.e.*

$$\hat{a} = \frac{\vec{k}_1 \times \vec{k}_2}{\left|\vec{k}_1 \times \vec{k}_2\right|} \quad . \tag{1}$$

The relationship of vectors $\vec{k}_1$, $\vec{k}_2$, and $\hat{a}$ is shown in a diagrammatic perspective view in FIG. **1b**. Component $\Delta\vec{k}_{1\perp}$ is orthogonal to $\vec{k}_1$ and orthogonal to unit vector $\hat{a}$, *i.e.* parallel to $\hat{k}_1 \times \hat{a}$ where $\hat{k}_1 = \vec{k}_1 / k_1$. The relationship of vectors $\vec{k}_1$, $\hat{a}$, and $\hat{k}_1 \times \hat{a}$ is shown in a diagrammatic perspective view in FIG. **1c**. $\Delta\vec{k}_{1\|}$ and $\Delta\vec{k}_{1\perp}$ are shown in diagrammatic perspective views in FIGS. **2** and **3**, respectively.

Infinitesimal changes $\Delta\vec{k}_{2\|}$ and $\Delta\vec{k}_{2\perp}$ corresponding to infinitesimal changes $\Delta\vec{k}_{1\|}$ and $\Delta\vec{k}_{1\perp}$, respectively, have the following properties for the optical system exhibiting the type T_{Ret} transformation properties:

(1) $\Delta\vec{k}_{2\|}$ is parallel to vector $\hat{a}$ and has a direction opposite to that of $\Delta\vec{k}_{1\|}$ and

(2) $\Delta\vec{k}_{2\perp}$ is orthogonal to both $\vec{k}_2$ and unit vector $\hat{a}$, *i.e.* parallel to $\hat{k}_2 \times \hat{a}$, $\hat{k}_2 = \vec{k}_2 / k_2$, with the additional condition that the direction of $\Delta\vec{k}_{2\perp} \times \vec{k}_2$ is the same as the direction of $\Delta\vec{k}_{1\perp} \times \vec{k}_1$.

The relationship of vectors $\vec{k}_2$, $\hat{a}$, and $\hat{k}_2 \times \hat{a}$ is shown in a diagrammatic perspective view in FIG. **1d**. The relationship of vectors $\Delta\vec{k}_{1\|}$ and $\Delta\vec{k}_{2\|}$ is shown in a diagrammatic perspective view in FIG. **2**. The relationship

16

of vectors $\Delta\vec{k}_{1\perp}$ and $\Delta\vec{k}_{2\perp}$ is shown in a diagrammatic perspective view in FIG. **3**.

The first embodiment of an optical system in accordance with the present invention exhibits both polarization preserving eigenmodes and the type T_{Ret} transformation properties. The first embodiment is shown as a diagrammatic perspective view in FIG. **4** where it is designated generally at **10**. Optical system **10** of the first embodiment comprises a Porro prism **20** and a right angle prism **30**.

An input beam **71** enters optical system **10** and exits optical system **10** as output beam **72** (see FIG. **4**). The path of input beam **71** through optical system **10** is shown in FIG. **4**. Input beam **71** enters Porro prism **20** at a surface at normal incidence after which it is reflected sequentially by a first surface and then a second surface of Porro prism **20**, enters right angle prism **30**, is reflected by a hypotenuse surface of right angle prism **30**, and exits right angle prism **30** as output beam **72** at a surface at normal incidence. The planes of incidence at the first and second surfaces of Porro prism **20** are parallel one with the other and orthogonal to the plane of incidence at the hypotenuse surface of right angle prism **30**.

There are two polarization preserving eigenmodes of the first embodiment wherein the input polarization states of the two eigenmodes are parallel and orthogonal to the planes of incidence at the first and second surfaces of Porro prism **20**. The corresponding output polarization states of the two polarization preserving eigenmodes are orthogonal and parallel to the plane of incidence of the

hypotenuse surface of right angle prism **30**, respectively. The eigenmodes are polarization preserving since the polarization states of the eigenmodes are either parallel to or orthogonal to the respective planes of incidence for each reflection and refraction in optical system **10**.

The transformation properties of optical system **10** with respect to changes in direction of propagation of output **72** that result from changes in direction of propagation of input beam **71** are the same as the properties of the type T_{Ret} transformation properties. This will be evident to those skilled in the art upon mapping the effects of changes in the direction of propagation of input beam **71** through optical system **10**.

The second embodiment of an optical system in accordance with the present invention exhibits both polarization preserving eigenmodes and the type T_{Ret} transformation properties. The second embodiment is shown as a diagrammatic perspective view in FIG. **5** where it is designated generally at **110**. Optical system **110** comprises a Porro prism **120** and a trapezoid prism **130**.

An input beam **171** enters optical system **110** and exits optical system **110** as output beam **172** (see FIG. **5**). The path of input beam **171** through optical system **110** is shown in FIG. **5**. Input beam **171** enters Porro prism **120** at a surface at normal incidence after which it is reflected sequentially by a first surface and then a second surface of Porro prism **120**, enters trapezoidal prism **130**, is reflected by a bottom surface of trapezoid prism **130**, and exits trapezoidal prism **130** at an exit surface as output beam **172**. The lengths of the entrance and exit surfaces

of trapezoidal prism **130** may be equal or not equal according to requirements of an end use application.

The planes of incidence at the first and second surfaces of Porro prism **120** are parallel and orthogonal to the plane of incidence at the surface of trapezoidal prism **130**. The planes of incidence at the surface and at the exit surface of trapezoidal prism **130** are parallel. The directions of propagation of input beam **171** and output beam **172** are generally neither parallel or orthogonal.

There are two polarization preserving eigenmodes of the second embodiment wherein the input polarization states of the two polarization preserving eigenmodes are parallel and orthogonal to the planes of incidence at the first and second surfaces of Porro prism **120**. The corresponding output polarization states of the two polarization preserving eigenmodes are orthogonal and parallel to the plane of incidence at the exit surface of trapezoid prism **130**, respectively. The eigenmodes are polarization preserving since the polarization states of the eigenmodes are either parallel to or orthogonal to the respective planes of incidence for each reflection and refraction in optical system **110**.

The transformation properties of optical system **110** with respect to changes in direction of propagation of output **172** that result from changes in direction of propagation of input beam **171** are the same as the properties of the type T_{Ret} transformation. This will be evident to those skilled in the art upon mapping the effects of changes in the direction of propagation of input beam **171** through optical system **110**.

The third embodiment of an optical system in accordance with the present invention exhibits both polarization preserving eigenmodes and the type T_{Ret} transformation properties. The third embodiment is shown as a diagrammatic perspective view in FIG. **6** where it is designated generally at **210**. Optical system **210** of the third embodiment comprises a Porro prism **220** and an inversion prism **230**.

An input beam **271** enters optical system **210** and exits optical system **210** as output beam **272** (see FIG. **6**). The path of input beam **271** through optical system **210** is shown in FIG. **6**. Input beam **271** enters Porro prism **220** at a surface at normal incidence after which it is reflected sequentially by a first surface and then a second surface of Porro prism **220**, exits Porro prism **220** at an exit surface and enters inversion prism **230** at an entrance surface, is reflected by a first, second, and third surface of inversion prism **230**, and exits inversion prism **230** at an exit surface as output beam **272**. The planes of incidence at the first and second surfaces of Porro prism **270** are parallel and orthogonal to the planes of incidence at the first, second, and third surfaces of inversion prism **230**. The planes of incidence at the first, second, and third surfaces, the entrance surface, and at the exit surface of the inversion prism are parallel. The directions of propagation of input beam **271** and output beam **272** may be parallel or not parallel according to requirements of an end use application.

There are two polarization preserving eigenmodes of the third embodiment wherein the input polarization states of the two polarization preserving eigenmodes are parallel

20

and orthogonal to the planes of incidence at the first and second surfaces of the Porro prism **220**. The corresponding output polarization states of the two polarization preserving eigenmodes are orthogonal and parallel to the plane of incidence of the first, second, and third surfaces of inversion prism **230**, respectively. The eigenmodes are polarization preserving since the polarization states of the eigenmodes are either parallel to or orthogonal to the respective planes of incidence for each reflection and refraction in optical system **210**.

The transformation properties of optical system **210** with respect to changes in direction of propagation of output **272** that result from changes in direction of propagation of input beam **271** are the same as the properties of the type T_{Ret} transformation. This will be evident to those skilled in the art upon mapping the effects of changes in the direction of propagation of input beam **271** through optical system **210**.

The fourth embodiment of an optical system in accordance with the present invention exhibits both polarization preserving eigenmodes and the type T_{Ret} transformation properties. The fourth embodiment is shown as a diagrammatic perspective view in FIG. **7** where it is designated generally at **310**. Optical system **310** comprises a right angle prism **320**, Porro prism **330**, and a penta prism **340**. Note that a subsystem of optical system **310** comprising right angle prism **320** and Porro prism **330** exhibits both polarization preserving eigenmodes and the type T_{Ret} transformation properties, the subsystem being equivalent to optical system **10** of the first embodiment.

An input beam **371** enters optical system **310** and exits optical system **310** as output beam **372** (see FIG. **7**). The path of input beam **371** through optical system **310** is shown in FIG. **7**. Input beam **371** enters right angle prism **320** at a surface at normal incidence after which it is reflected by a hypotenuse surface of right angle prism **320**, exits right angle prism **320** at an exit surface, enters Porro prism **330** at an entrance surface and is reflected sequentially by a first surface and then a second surface of Porro prism **330**, and exits Porro prism **330** at an exit surface. After exiting Porro prism **320**, beam **371** enters penta prism **340** at an entrance surface after which it is reflected by a first surface and a second surface of penta prism **340** and exits penta prism **340** at an exit surface at normal incidence as output beam **372**.

The plane of incidence at the hypotenuse surface of the right angle prism **320** is orthogonal to the parallel planes of incidence at the first and second surfaces of Porro prism **330**. The planes of incidence at the first and second surfaces of Porro prism **330** are orthogonal to the planes of incidence at the first and second surfaces of penta prism **340**. The directions of propagation of input beam **371** and output beam **372** are parallel.

There are two polarization preserving eigenmodes of the fourth embodiment wherein the input polarization states of the two polarization preserving eigenmodes are parallel and orthogonal to the plane of incidence at the hypotenuse surface of right angle prism **370**. The corresponding output polarization states of the two polarization preserving eigenmodes are parallel and orthogonal to the planes of incidence of the first and

second surfaces of penta prism **340**, respectively. The eigenmodes are polarization preserving since the polarization states of the eigenmodes are either parallel to or orthogonal to the respective planes of incidence for each reflection and refraction in optical system **310**.

The transformation properties of optical system **310** with respect to changes in direction of propagation of output beam **372** that result from changes in direction of propagation of input beam **371** are the same as the properties of the type T_{Ret} transformation. This will be evident to those skilled in the art upon mapping the effects of changes in the direction of propagation of input beam **371** through optical system **310**.

The fifth embodiment of an optical system in accordance with the present invention exhibits both polarization preserving eigenmodes and the type T_{Ret} transformation properties. The fifth embodiment is shown as a diagrammatic perspective view in FIG. **8** where it is designated generally at **410**. Optical system **410** comprises two beam splitters and a Porro prism **430**. The first beam splitter comprises a right angle prism **421** and a trapezoidal prism **422** with a beam-splitting interface **423**. The second beam splitter comprises a prism **441** and a right angle prism **442** with a beam-splitting interface **443**.

The fifth embodiment comprises a subsystem of optical elements that also exhibits both polarization preserving eigenmodes and the type T_{Ret} transformation properties. The subsystem of optical elements comprises trapezoidal prism **422** with beam splitter interface **423**, Porro prism **430**, and prism **441** with beam-splitting interface **443**.

Input beams **471** and **472** enter optical system **410** and exit optical system **410** as output beams **475** and **476**, respectively (see FIG. **8**). The paths of input beam **471** and **472** through optical system **410** are shown in FIG. **8**.

Input beams **471** and **472** enter the first beam splitter with planes of polarization parallel or orthogonal to the respective planes of incidence at beam-splitting interface **423**. Input beams **471** and **472** are reflected by beam-splitting interface **423**, then exit trapezoidal prism **422** and enter Porro prism **430** at a surface at normal incidence, are reflected sequentially at a first surface and then at second surface of Porro prism **430**, and exit Porro prism **430** at a surface at normal incidence as beams **473** and **474**, respectively. The planes of incidence of beams **471** and **472** at the first and second surfaces of Porro prism **430** are either orthogonal or parallel to the respective planes of incidence at the beam-splitting interface **423**.

Note that the subsystem of optical system **410** comprising trapezoidal prism **422** and Porro prism **430** exhibits both polarization preserving eigenmodes and the type T_{Ret} transformation properties, the subsystem being equivalent to optical system **110** of the second embodiment. Beams **471** and **472** are optical beams that meet the conditions to be classified as being eigenmodes of the subsystem and optical beams of the subsystem for which type T_{Ret} transformations apply.

Beams **473** and **474** next enter prism **441** at a entrance surface at normal incidence, sequentially reflected by a first surface and then by beam-splitting interface **443**, and exit prism **441** at an exit surface at normal incidence

24

as output beams **475** and **476**, respectively. The planes of polarization of beams **473** and **474** are parallel or orthogonal to the respective planes of incidence at the first surface and beam-splitting surfaces of prism **441**.

There are two polarization preserving eigenmodes of the fifth embodiment wherein the input polarization states of the two eigenmodes are parallel and orthogonal to the plane of incidence at the beam splitter interface of trapezoidal prism **422**. The corresponding output polarization states of the two polarization preserving eigenmodes are parallel and orthogonal to the planes of incidence of the first and beam-splitting surfaces of prism **441**, respectively. The eigenmodes are polarization preserving since the polarization states of the eigenmodes are either parallel to or orthogonal to the respective planes of incidence for each reflection and refraction in optical system **410**.

The transformation properties of optical system **410** with respect to changes in direction of propagation of output beams **475** and **476** that result from changes in direction of propagation of input beams **471** and **472**, respectively, are the same as the properties of the type T_{Ret} transformation. This will be evident to those skilled in the art upon mapping the effects of changes in the direction of propagation of input beams **471** and **472** through optical system **410**.

Having described a number of embodiments of polarization preserving optical systems in accordance with the invention, embodiments in which such optical systems may be incorporated to form interferometers will now be described.

A sixth embodiment in accordance with the present invention is a plane mirror interferometer **510** shown in diagrammatic perspective view in FIG. **9**. The plane mirror interferometer **510** comprises a polarizing beam splitter **513**, a quarter-wave phase retardation plate **551**, object mirror **553**, and a first and second polarization preserving optical systems designated generally at **511** and **512**, respectively. The components of the polarizing beam splitter **513** are prisms **521** and **522** with a polarizing interface **523**. The description of each of the first and second polarization preserving optical systems is the same as the description given for the polarization preserving optical system of the fourth embodiment shown in FIG. **7**.

The input beams comprise two orthogonally polarized beams **571** and **572**, beam **571** serving as the measurement beam and beam **572** as the reference beam. The polarizing beam splitter **513** reflects the reference beam **572** and transmits the measurement beam **571** at polarizing interface **523**. The reference beam returns to the output as beam **574** after being reflected by the second polarization preserving optical system **512** and again by the polarizing beam splitter **513**. The measurement beam returns to the output as beam **573** after being reflected twice from object mirror **553**, transmission through phase retardation plate **551** twice for each round trip to object mirror **553**, being reflected by the first polarization preserving optical system at **511**, and being transmitted twice and reflected twice by the polarizing beam splitter **513**.

Input beams **571** and **572** and output beams **573** and **574** are shown in FIG. **9** as being spatially separated. It will be evident to those skilled in the art that input beams

26

571 and **572** can alternatively be arranged to be coextensive as well as the output beams **573** and **574** without departing from the scope and the spirit of the invention.

The seventh embodiment in accordance with the present invention is a high stability plane mirror interferometer **600** shown in diagrammatic perspective view in FIG. **10**. The high stability plane mirror interferometer **600** comprises a polarizing beam splitter **602**, quarter-wave phase retardation plates **651** and **652**, object mirror **653**, reference mirror **654**, and a polarization preserving optical system designated generally at **611**. The components of the polarizing beam splitter **602** are prisms **621** and **622** with a polarizing interface **623**. The description of the polarization preserving optical system is the same as the description given for the polarization preserving optical system of the fourth embodiment shown in FIG. **7**.

An input beam **671** comprises two orthogonally polarized beam components. The polarizing beam splitter **602** reflects one component of input beam **671** as a reference beam and transmits the second component of input beam **671** as a measurement beam at polarizing interface **623**. The reference beam returns as a reference beam component of output beam **673** after being reflected twice by the reference mirror **654**, transmission through phase retardation plate **652** twice for each round trip to reference mirror **654**, being reflected by the polarization preserving optical system at **611**, and being reflected twice and transmitted twice by the polarizing beam splitter **602**. The measurement beam returns as a

measurement beam component of output beam **673** after being reflected twice from object mirror **653**, transmission through phase retardation plate **651** twice for each round trip to object mirror **653**, being reflected by the polarization preserving optical system at **611**, and being transmitted twice and reflected twice by the polarizing beam splitter **602** .

The reference and measurement beam components of input beam **671** and the reference and measurement beam components of output beam **673** are shown in FIG. **10** as being coextensive, respectively. It will be evident to those skilled in the art that the reference and measurement beam components of input beam **671** can alternatively be arranged to be spatially separated as well as the reference and measurement beam components of output beam **673** without departing from the scope and the spirit of the invention.

Reference is now made to **Fig. 10a** that shows a variant of the interferometer **600** of **Fig. 10** and is designated generally as **600a**. Interferometer **600a** differs in operation from interferometer **600** by virtue of the fact that it provides for four passes of its reference and object beams to enhance sensitivity, the reference and object beams are spatially separated to reduce polarization mixing, and the input and output beam locations are vertically separated on the same side of the input facet of the polarization beam splitter **602**. Otherwise, both interferometers have elements in common, and those elements carry the same numerical designation in **Fig. 10a** as they have in **Fig. 10**. As seen in **Fig. 10a**, there are two spatially separated input beams **660** that are

orthogonally polarized with respect to one another. Input beams **660** travel through interferometer **600a** in a fashion similar to the corresponding beams in **Fig. 10** except that in **Fig. 10**, the orthogonally polarized beams are overlapped. In addition, at what was the output in **Fig. 10**, the corresponding beams in interferometer **600a** are intercepted by prismatic element **664** that operates to reintroduce them into the polarizing beam splitter **602** after which they undergo two additional passes through interferometer **600a** to emerge as output beams **662**. Input beams **660** may be provided from a single laser whose output can be split or can originate from separate lasers, and output beams **662** may be combined for subsequent signal processing(See **Fig. 16a** for examples of splitting and combining optics). It will also be evident that input beams of different wavelengths may be provided as pairs of spatially separated beams which wavelengths may be harmonically related and be provided by frequency doubling techniques or, alternatively, the input beams may be spatially separated with each having components of different wavelength but with the same polarization.

The eighth embodiment in accordance with the present invention is a high stability plane mirror interferometer **700** shown in diagrammatic perspective view in FIG. **11**. The eighth embodiment exhibits reduced cyclic errors and comprises a plane mirror interferometer with a split quarter-wave phase retardation plate in a measurement leg. Many elements of the eighth embodiment form like functions as elements of the seventh embodiment shown in the FIG. **10**, the element number of an eighth-embodiment element being 100 larger than the element number of a

corresponding seventh-embodiment element. The function of phase retardation plate **651** of the seventh embodiment is achieved in the eighth embodiment by two phase retardation plates **751A** and **751B**.

Phase retardation plates **751A** and **751B** are tilted one with respect to the other so as to eliminate a potential source of cyclic errors. The potential source of cyclic errors is a generation of a spurious beam by two ghost reflections from a phase retardation plate such as phase retardation plate **651** found in the seventh embodiment. The description of the reduction of the cyclic errors in the eighth embodiment is the same as corresponding description given in copending commonly owned US Patent Application 09/384,609 ~~(Attorney Docket Number 0201/US)~~ entitled "INTERFEROMETER HAVING REDUCED GHOST BEAM EFFECTS" by Peter de Groot the contents of which are incorporated herein by reference. The function of the phase retardation plates may be strategically achieved by other surfaces of an interferometer as, for example, by tilting selected surfaces of a polarizing beam splitter.

The remaining description of the eighth embodiment is the same as the corresponding portion of the description given for the seventh embodiment.

The ninth embodiment in accordance with the present invention is a differential plane mirror interferometer **800** shown in diagrammatic perspective view in FIG. **12** and in a diagrammatic side view in FIG **13**. The differential plane mirror interferometer **800** comprises a shear plate **816**, a polarizing beam splitter **802**, quarter-wave phase retardation plate **851**, object mirror **853**, reference mirror **854**, and a polarization preserving optical system

designated generally at **811**. The components of the polarizing beam splitter **802** are prisms **821** and **822** with a polarizing interface **823**. The description of the polarization preserving optical system is the same as the description given for the polarization preserving optical system of the fourth embodiment shown in FIG. **7**.

An input beam **871** comprises two orthogonally polarized beam components. Shear plate **816** transmits one polarization component of input beam **871** as a measurement beam **872**. The second polarization component of input beam **871** is first transmitted by shear plate **816**, after two internal reflections, and then transmitted by a half-wave phase retardation plate **855** as a reference beam **873**. Half-wave phase retardation plate **855** is orientated so as to rotate the plane of polarization of reference beam **873** to be parallel to the plane of polarization of measurement beam **872** and parallel to the plane of FIG. **13**. Measurement beam **872** and reference beam **873** are spatially separated.

Measurement beam **872** returns as a measurement beam **874** after being reflected twice by object mirror **853**, transmission through phase retardation plate **851** twice for each round trip to object mirror **853**, being reflected by the polarization preserving optical system **811**, and being reflected twice and transmitted twice by the polarizing beam splitter **802**. Reference mirror **854** comprises two apertures (see FIG. **12**) through which the measurement beam passes in transit to and from object mirror **853**.

Reference beam **873** returns as a reference beam **875** after being reflected twice from reference mirror **854**, transmission through phase retardation plate **851** twice for

each round trip to reference mirror **854**, being reflected by the polarization preserving optical system **811**, and being reflected twice and transmitted twice by the beam splitter **802**.

Next, measurement beam **874** is transmitted by half-wave phase retardation plate **856** and then transmitted by shear plate **816**, after two internal reflections, as a measurement beam component of output beam **876**. Half-wave phase retardation plate **856** is orientated so as to rotate the plane of polarization of the measurement beam component of output beam **876** by 90° with respect to the plane of polarization of measurement beam **874**. Reference beam **875** is transmitted by shear plate **816** as a reference beam component of output beam **876**. The measurement and reference beam components of output beam **876** are orthogonally polarized.

The remaining description of the ninth embodiment is the same as corresponding portions of the description given for the seventh embodiment.

The tenth embodiment in accordance with the present invention is a high stability plane mirror interferometer **902** shown in diagrammatic perspective view in FIG. **14**. The high stability plane mirror interferometer **900** of the tenth embodiment is configured for use in applications requiring a column reference.

Many elements of the tenth embodiment form like functions as elements of the seventh embodiment shown in the FIG. **10**, the element number of an tenth-embodiment element being 200 larger than the element number of a corresponding eighth-embodiment element. Mirror **955** reflects the reference beam in transit between reference

mirror **954** and a polarizing beam splitter **902**. Reference mirror **954** is attached to a reference object such as a column containing an imaging system for focusing radiation onto a wafer and the measurement mirror **953** is attached to a wafer stage as a measurement object supporting the wafer wherein the imaging system, radiation, wafer, and wafer stage are components of a lithography tool used in the manufacture of integrated circuits, such lithography apparatus to be described further hereinafter.

The remaining description of the tenth embodiment is the same as corresponding portion of the description given for the eighth embodiment.

An eleventh embodiment in accordance with the present invention is a dual linear/angular displacement interferometer system **1000** shown in diagrammatic view in FIG. **15**. Certain subsystems of the dual linear/angular displacement interferometer system **1000** exhibit both polarization preserving eigenmodes and the type T_{Ret} transformation properties. A dual linear/angular displacement interferometer shown as element **1010** in FIG. **15** comprises two interferometers wherein the outputs of the two interferometers are combined to yield a linear displacement and an angular displacement of an object mirror. Dual linear/angular displacement interferometer **1010** further comprises a high stability plane mirror interferometer for each of the two interferometers and the two interferometers have a common polarizing beam splitter **1002**, a common object mirror **1053**, a common reference mirror **1054**, common quarter-wave phase retardation plates **1051** and **1052**, and a common source **1014**. The polarizing

beam splitter **1002** comprises prisms **1021** and **1022** with a polarizing interface **1023**.

The high stability plane mirror interferometers are each of the polarization preserving type of the seventh embodiment shown in FIG. **10**. The high stability plane mirror interferometers comprise polarization preserving optical systems generally shown at **1011** and **1012**. The polarization preserving optical systems are the same as the one shown in FIG. **7** of fourth embodiment.

Common source **1014** generates beam **1071**. Source **1014** is preferably a source such as a single frequency laser and acousto-optical modulator arranged to generate beam **1071** with two orthogonally polarized components having different optical frequencies. The two orthogonal planes of polarization are orientated at angles of 45° to the plane of FIG. **15**. Beam **1071** is incident on non-polarizing beam splitter **1016A** and a first portion thereof is transmitted as a first input beam for one of the two high stability plane mirror interferometers. A second portion of beam **1071** incident on beam splitter **1016A** is reflected by beam splitter **1016A** and then reflected by mirror **1016B** as a second input beam **1072** for the second of the two high stability plane mirror interferometers.

The propagation of the first input beam and the second input beam **1072** through the dual linear/angular displacement interferometer **1010** is shown in FIG. **15** and exit interferometer **1010** as output beams **1073** and **1074**, respectively. Output beams **1073** and **1074** each have orthogonally polarized measurement and reference beam components. Output beam **1073** is transmitted by polarizer **1055** as a mixed beam that is detected by detector **1061**

preferably by the photoelectric effect to produce a first electrical interference signal or a first heterodyne signal. Output beam **1074** is transmitted by polarizer **1056** as a mixed beam that is detected by detector **1062** preferably by the photoelectric effect to produce a second electrical interference signal or a second heterodyne signal. The first and second heterodyne signals are transmitted to electronic processor and computer **1065** to generate a corresponding first and second relative linear displacements. The first and second relative linear displacements are averaged to produce a relative linear displacement **1075** of object mirror **1053** and subtracted one from the other wherein the resulting difference is used to produce a relative angular displacement **1076** of object mirror **1053**.

The remaining description of the eleventh embodiment is the same as corresponding portions of the description given for the seventh embodiment.

A variant of the eleventh embodiment in accordance with the present invention comprises a dual linear/angular displacement interferometer system. The variant of eleventh embodiment exhibits reduced sources of certain cyclic errors and certain subsystems of the dual linear/angular displacement interferometer system exhibit both polarization preserving eigenmodes and the type T_{Ret} transformation properties. The variant of the eleventh embodiment comprises two high stability plane mirror wherein each of the high stability plane mirror interferometers is of the high stability plane mirror interferometer type shown in FIG. **11** of the eighth embodiment.

The remaining description of the variant of the eleventh embodiment is the same as corresponding portions of the descriptions given for the eighth and eleventh embodiments.

It will be evident to one skilled in the art that the eleventh embodiment and its variant may be readily extended to simultaneously measure multiple degrees of freedom in displacement and angle and that such measurements may be made along orthogonal or other directions if desired. This may be done, for example, through the use of a plurality of devices in the form of the eleventh embodiment and/or through additional interferometer sections added to the eleventh embodiment or both.

Other examples of optical systems exhibiting polarization preserving eigenmodes and the type T_{Ret} transformation properties are optical systems of a twelfth embodiment in accordance with the present invention. The twelfth embodiment comprises a differential plane mirror interferometer **1100** with a dynamic element **1155** as shown in diagrammatic perspective view in FIG. **16a**. The orientation of dynamic element **1155** is servoed to maintain the measurement beam perpendicular to an object mirror **1153**.

Input beam **1171** comprises two orthogonally polarized components having frequencies different one for the other. Input beam **1171** enters a first beam splitter comprising a right angle prism **1141** and a rhomboidal prism **1142** with a polarizing interface **1143**. A first portion of input beam **1171** incident on polarizing interface **1143** is transmitted as a measurement beam **1173**. A second portion of input

376

beam **1171** incident on polarizing interface **1143** is reflected and exits the first beam splitter, after an internal reflection, as a reference beam **1174**.

Measurement beam **1173** and reference beam **1174** exit the differential plane mirror **1100** interferometer as output measurement and reference beams **1175** and **1176**, respectively. Propagation of measurement beam **1173** and reference beam **1174** through the differential plane mirror interferometer **1100** is shown in FIG. **16a**. The orientation of dynamic mirror **1155** is controlled by transducers **1156A**, **1156B**, and **1156C**. Output measurement and reference beams **1175** and **1176** are combined into a mixed output beam by a second beam splitter comprising right angle prism **1144**, rhomboidal prism **1145**, and beam splitting interface **1146**. The output beam is received by detector and signal processor **1160** that operates to provide information, *e.g.*, such as phase detection and phase analysis, about linear and/or angular displacements of object mirror **1153** and information relating to the alignment of beams, *e.g.*, such as detection of changes in direction of propagation of the measurement beam component of the output beam, used for the servo control of dynamic mirror **1155**. Along with other interferometers having dynamic elements, operation of the differential plane mirror interferometer **1100** is further described in copending, commonly owned US Patent Application 09/384,851 filed 8/27/99 ~~(Attorney Docket Number 09712/040001)~~ entitled "Interferometry System Having A Dynamic Beam Steering Assembly For Measuring Angle and Distance" by Henry A. Hill, which copending application is incorporated herein by reference.

An optical subsystem indicated as **1100** in FIG. **16a**, quarter-wave phase retardation plate **1151**, and reference mirror **1154** exhibit, as a first optical system, polarization preserving eigenmodes and the type T_{Ret} transformation properties for input reference beam **1174**. Also optical subsystem **1100**, quarter-wave phase retardation plate **1151**, object mirror **1153**, and dynamic element **1155** for a fixed orientation exhibit, as a second optical system, polarization preserving eigenmodes and the type T_{Ret} transformation properties for input measurement beam **1174**

Optical subsystem **1100** comprises a modified Porro prism **1121** and prisms **1125**, **1129**, and **1133** shown schematically in FIGS. **16b**, **16c**, **16d**, and **16e**, respectively. An interface comprising surfaces **1128** and **1130** is a polarizing beam splitter interface.

There are two polarization preserving eigenmodes of the first optical system wherein the input polarization states of the two eigenmodes are orthogonal and parallel, respectively, to the plane of incidence at surface **1136** of prism **1133**. The corresponding output polarization states of the two polarization preserving eigenmodes are orthogonal and parallel to the plane of incidence at surface **1123** of prism **1121**. The eigenmodes are polarization preserving since the polarization states of the eigenmodes are either parallel to or orthogonal to the respective planes of incidence for each reflection and refraction in the first optical system.

There are also two polarization preserving eigenmodes of the second optical system wherein the input polarization states of the two eigenmodes are orthogonal

and parallel, respectively, to the plane of incidence at a first surface of dynamic element **1155**. The plane of incidence at the first surface of dynamic element **1155** is parallel to the plane of incidence of beams of the eigenmodes at surface **1123** of Porro prism **1121**. The corresponding output polarization states of the two polarization preserving eigenmodes are parallel and orthogonal, respectively, to the planes of incidence of a surface of dynamic element **1155**. The eigenmodes are polarization preserving since the polarization states of the eigenmodes are either parallel to or orthogonal to the respective planes of incidence for each reflection and refraction in the second optical system.

The transformation properties of the first and second optical systems of the twelfth embodiment with respect to changes in direction of propagation of output beams **1175** and **1176** that result from changes in direction of propagation of input beams **1173** and **1174**, respectively, are the same as the properties of the type T_{Ret} transformation. This will be evident to those skilled in the art upon mapping the effects of changes in the direction of propagation of input beams **1173** and **1174** through the first and second optical systems.

A thirteenth embodiment in accordance with the present invention exhibits enhanced polarizing beam splitter properties, polarization preserving eigenmodes, and the type T_{Ret} transformation properties. The use of an optical system in an interferometer exhibiting enhanced polarizing beam splitter properties can for example lead to reduced cyclic errors in phase differences measured with the interferometer.

The thirteenth embodiment is shown as a diagrammatic perspective view in FIG. **17** and comprises a beam splitter and a polarization preserving optical system shown generally at **1211**. The beam splitter comprises prisms **1221** and **1222** with a polarizing beam splitting interface **1223**. The polarization preserving optical system comprises the polarization preserving optical system shown in FIG. **7** of the fourth embodiment with polarizing properties for certain reflecting surfaces. The certain reflecting surfaces can comprise one or more of those surfaces of the right angle prism, the Porro prism, and the penta prism of the polarization preserving optical system at which beams corresponding to eigenmodes (of the polarization preserving optical system) are internally reflected. For the thirteenth embodiment, the certain reflecting surfaces comprise the internally reflecting surfaces of the Porro prism and the penta prism of the polarization preserving optical system.

Optical flats **1231**, **1232**, **1233**, and **1234** are either cemented onto the internally reflecting surfaces of the Porro prism and the penta prism (see FIG. **17**) with an optical grade cement or by optical contacting. For optical beams entering and exiting the thirteenth embodiment that are in the ultra violet, the preferred attachment method for the optical flats is optical contacting. Before cementing or optical contacting the optical flats, multi-layer thin film coatings are applied to the surfaces of the optical flats and/or corresponding surfaces of the Porro prism and the penta prism so that after the cementing or contacting procedure, the

respective interfaces become polarizing surfaces for the eigenmodes of polarization preserving retroreflector.

The polarizing properties of corresponding portions of the polarizing surfaces are chosen so that for an eigenmode reflected (transmitted) by a portion of polarizing interface **1223** of the polarizing beam splitter, the corresponding portions of the polarizing surfaces of the polarization preserving optical system preferably reflect (reflect) the eigenmode. As a consequence, the polarizing surfaces serve as "polarization filters" in that the polarizing surfaces transmit spurious beams generated by the reflection (transmission) of unwanted beams by polarizing interface **1223** of the polarizing beam splitter.

It will be evident on examination of respective figures that the polarizing beam splitter and the polarizing preserving optical system of the thirteenth embodiment comprise subsystems of the sixth, seventh, eighth, ninth, ten, eleventh, and twelfth embodiments of the present invention.

The polarization filtering properties of polarization preserving optical systems may also be augmented and/or achieved by replacing one or more components of the polarization preserving optical systems with corresponding components made from birefringent mediums, *e.g.* quartz, calcite, or lithium niobate, such that the corresponding components become polarizers.

A penta prism polarizer **1340** is shown in FIG. **18** comprising a birefringent medium. The optic-axis **1341** of the birefringent medium is parallel to the plane of FIG. **18** and orientated at an angle β to a surface of modified

penta prism **1340** as shown in FIG. **18**. The orientation of the surfaces of the penta prism and the angle β are selected so that a desired polarization component of an input beam propagates through the penta prism and exits the penta prism as a polarization preserving eigenmode of the penta prism which comprises polarization filtering. An example of penta prism polarizer is described in an article by H. Lotem and K. Rabinovitch entitled "Penta prism laser polarizer" in *Appl. Optics* **32**(12) pp 2017-2020 (1993).

An optical system exhibiting polarization preserving eigenmodes and further comprising polarization filtering can be employed to produce interferometers that work simultaneously at two widely separated wavelengths, in particular two harmonically related wavelengths. The measurement and reference paths for the two wavelengths can be coextensive in respective portions of the interferometer, in particular at a polarizing beam splitter interface, with significantly reduced sources of cyclic errors for both wavelengths compared to sources of cyclic errors in prior art interferometers.

The interferometry systems described above can be especially useful in lithography applications used for fabricating large scale integrated circuits such as computer chips and the like. Lithography is the key technology driver for the semiconductor manufacturing industry. Overlay improvement is one of the five most difficult challenges down to and below 100 nm line widths (design rules), see for example the *Semiconductor Industry Roadmap*, p82 (1997). Overlay depends directly on the performance, *i.e.* accuracy and precision, of the distance

measuring interferometers used to position the wafer and reticle (or mask) stages. Since a lithography tool may produce $50-100M/year of product, the economic value from improved performance distance measuring interferometers is substantial. Each 1% increase in yield of the lithography tool results in approximately $1M/year economic benefit to the integrated circuit manufacturer and substantial competitive advantage to the lithography tool vendor.

The function of a lithography tool is to direct spatially patterned radiation onto a photoresist-coated wafer. The process involves determining which location of the wafer is to receive the radiation (alignment) and applying the radiation to the photoresist at that location (exposure).

To properly position the wafer, the wafer includes alignment marks on the wafer that can be measured by dedicated sensors. The measured positions of the alignment marks define the location of the wafer within the tool. This information, along with a specification of the desired patterning of the wafer surface, guides the alignment of the wafer relative to the spatially patterned radiation. Based on such information, a translatable stage supporting the photoresist-coated wafer moves the wafer such that the radiation will expose the correct location of the wafer.

During exposure, a radiation source illuminates a patterned reticle, which scatters the radiation to produce the spatially patterned radiation. The reticle is also referred to as a mask, and these terms are used interchangeably below. In the case of reduction lithography, a reduction lens collects the scattered

radiation and forms a reduced image of the reticle pattern. Alternatively, in the case of proximity printing, the scattered radiation propagates a small distance (typically on the order of microns) before contacting the wafer to produce a 1:1 image of the reticle pattern. The radiation initiates photo-chemical processes in the photoresist that convert the radiation pattern into a latent image within the photoresist.

The interferometry systems described above are important components of the positioning mechanisms that control the position of the wafer and reticle, and register the reticle image on the wafer.

In general, the lithography system, also referred to as an exposure system, typically includes an illumination system and a wafer positioning system. The illumination system includes a radiation source for providing radiation such as ultraviolet, visible, x-ray, electron, or ion radiation, and a reticle or mask for imparting the pattern to the radiation, thereby generating the spatially patterned radiation. In addition, for the case of reduction lithography, the illumination system can include a lens assembly for imaging the spatially patterned radiation onto the wafer. The imaged radiation exposes photoresist coated onto the wafer. The illumination system also includes a mask stage for supporting the mask and a positioning system for adjusting the position of the mask stage relative to the radiation directed through the mask. The wafer positioning system includes a wafer stage for supporting the wafer and a positioning system for adjusting the position of the wafer stage relative to the imaged radiation. Fabrication of integrated circuits can

include multiple exposing steps. For a general reference on lithography, see, for example, J. R. Sheats and B. W. Smith, in *Microlithography: Science and Technology* (Marcel Dekker, Inc., New York, 1998), the contents of which are incorporated herein by reference.

The interferometry systems described above can be used to precisely measure the positions of each of the wafer stage and mask stage relative to other components of the exposure system, such as the lens assembly, radiation source, or support structure. In such cases, the interferometry system can be attached to a stationary structure and the measurement object attached to a movable element such as one of the mask and wafer stages. Alternatively, the situation can be reversed, with the interferometry system attached to a movable object and the measurement object attached to a stationary object.

More generally, the interferometry systems can be used to measure the position of any one component of the exposure system relative to any other component of the exposure system in which the interferometry system is attached, or supported by one of the components and the measurement object is attached, or is supported by the other of the components.

An example of a lithography scanner **1400** using an interferometry system **1426** is shown in Fig. **19a**. The interferometry system is used to precisely measure the position of a wafer within an exposure system. Here, stage **1422** is used to position the wafer relative to an exposure station. Scanner **1400** comprises a frame **1402**, which carries other support structures and various components carried on those structures. An exposure base

1404 has mounted on top of it a lens housing **1406** atop of which is mounted a reticle or mask stage **1416** used to support a reticle or mask. A positioning system for positioning the mask relative to the exposure station is indicated schematically by element **1417**. Positioning system **1417** can include, *e.g.*, piezoelectric transducer elements and corresponding control electronics. Although, it is not included in this described embodiment, one or more of the interferometry systems described above can also be used to precisely measure the position of the mask stage as well as other moveable elements whose position must be accurately monitored in processes for fabricating lithographic structures (see *supra* Sheats and Smith *Microlithography: Science and Technology*).

Suspended below exposure base **1404** is a support base **1413** that carries wafer stage **1422**. Stage **1422** includes a plane mirror for reflecting a measurement beam **1454** directed to the stage by interferometry system **1426**. A positioning system for positioning stage **1422** relative to interferometry system **1426** is indicated schematically by element **1419**. Positioning system **1419** can include, *e.g.*, piezoelectric transducer elements and corresponding control electronics. The measurement beam reflects back to the interferometry system, which is mounted on exposure base **1404**. The interferometry system can be any of the embodiments described previously.

During operation, a radiation beam **1410**, *e.g.*, an ultraviolet (UV) beam from a UV laser (not shown), passes through a beam shaping optics assembly **1412** and travels downward after reflecting from mirror **1414**. Thereafter, the radiation beam passes through a mask (not shown)

carried by mask stage **1416**. The mask (not shown) is imaged onto a wafer (not shown) on wafer stage **1422** via a lens assembly **1408** carried in a lens housing **1406**. Base **1404** and the various components supported by it are isolated from environmental vibrations by a damping system depicted by spring **1420**.

In other embodiments of the lithographic scanner, one or more of the interferometry systems described previously can be used to measure distance along multiple axes and angles associated for example with, but not limited to, the wafer and reticle (or mask) stages. Also, rather than a UV laser beam, other beams can be used to expose the wafer including, *e.g.*, x-ray beams, electron beams, ion beams, and visible optical beams.

In addition, the lithographic scanner can include a column reference in which interferometry system **1426** directs the reference beam to lens housing **1406** or some other structure that directs the radiation beam rather than a reference path internal to the interferometry system. The interference signal produce by interferometry system **1426** when combining measurement beam **1454** reflected from stage **1422** and the reference beam reflected from lens housing **1406** indicates changes in the position of the stage relative to the radiation beam. Furthermore, in other embodiments the interferometry system **1426** can be positioned to measure changes in the position of reticle (or mask) stage **1416** or other movable components of the scanner system. Finally, the interferometry systems can be used in a similar fashion with lithography systems involving steppers, in addition to, or rather than, scanners.

As is well known in the art, lithography is a critical part of manufacturing methods for making semiconducting devices. For example, U.S. Patent 5,483,343 outlines steps for such manufacturing methods. These steps are described below with reference to FIGS. **19b** and **19c**. FIG. **19b** is a flow chart of the sequence of manufacturing a semiconductor device such as a semiconductor chip (*e.g.* IC or LSI), a liquid crystal panel or a CCD. Step **1451** is a design process for designing the circuit of a semiconductor device. Step **1452** is a process for manufacturing a mask on the basis of the circuit pattern design. Step **1453** is a process for manufacturing a wafer by using a material such as silicon.

Step **1454** is a wafer process which is called a pre-process wherein, by using the so prepared mask and wafer, circuits are formed on the wafer through lithography. Step **1455** is an assembling step, which is called a post-process wherein the wafer processed by step **1454** is formed into semiconductor chips. This step includes assembling (dicing and bonding) and packaging (chip sealing). Step **1456** is an inspection step wherein operability check, durability check, and so on of the semiconductor devices produced by step **1455** are carried out. With these processes, semiconductor devices are finished and they are shipped (step **1457**).

FIG. **19c** is a flow chart showing details of the wafer process. Step **1461** is an oxidation process for oxidizing the surface of a wafer. Step **1462** is a CVD process for forming an insulating film on the wafer surface. Step **1463** is an electrode forming process for forming electrodes on the wafer by vapor deposition. Step **1464** is

an ion implanting process for implanting ions to the wafer. Step **1465** is a photoresist process for applying a photoresist (photosensitive material) to the wafer. Step **1466** is an exposure process for printing, by exposure, the circuit pattern of the mask on the wafer through the exposure apparatus described above. Step **1467** is a developing process for developing the exposed wafer. Step **1468** is an etching process for removing portions other than the developed photoresist image. Step **1469** is a photoresist separation process for separating the photoresist material remaining on the wafer after being subjected to the etching process. By repeating these processes, circuit patterns are formed and superimposed on the wafer.

The interferometry systems described above can also be used in other applications in which the relative position of an object needs to be measured precisely. For example, in applications in which a write beam such as a laser, x-ray, ion, or electron beam, marks a pattern onto a substrate as either the substrate or beam moves, the interferometry systems can be used to measure the relative movement between the substrate and write beam.

As an example, a schematic of a beam writing system **1500** is shown in FIG. **20**. A source **1510** generates a write beam **1512**, and a beam focusing assembly **1514** directs the radiation beam to a substrate **1516** supported by a movable stage **1518**. To determine the relative position of the stage, an interferometry system **1520** directs a reference beam **1522** to a mirror **1524** mounted on beam focusing assembly **1514** and a measurement beam **1526** to a mirror **1528** mounted on stage **1518**. Interferometry system **1520** can be

any of the interferometry systems described previously. Changes in the position measured by the interferometry system correspond to changes in the relative position of write beam **1512** on substrate **1516**. Interferometry system **1520** sends a measurement signal **1532** to controller **1530** that is indicative of the relative position of write beam **1512** on substrate **1516**. Controller **1530** sends an output signal **1534** to a base **1536** that supports and positions stage **1518**. In addition, controller **1530** sends a signal **1538** to source **1510** to vary the intensity of, or block, write beam **1512** so that the write beam contacts the substrate with an intensity sufficient to cause photophysical or photochemical change only at selected positions of the substrate. Furthermore, in some embodiments, controller **1530** can cause beam focusing assembly **1514** to scan the write beam over a region of the substrate, *e.g.*, using signal **1544**. As a result, controller **1530** directs the other components of the system to pattern the substrate. The patterning is typically based on an electronic design pattern stored in the controller. In some applications the write beam patterns a photoresist coated on the substrate and in other applications the write beam directly patterns, *e.g.*, etches, the substrate.

An important application of such a system is the fabrication of masks and reticles used in the lithography methods described previously. For example, to fabricate a lithography mask an electron beam can be used to pattern a chromium-coated glass substrate. In such cases where the write beam is an electron beam, the beam writing system encloses the electron beam path in a vacuum. Also, in

cases where the write beam is, *e.g.*, an electron or ion beam, the beam focusing assembly includes electric field generators such as quadrapole lenses for focusing and directing the charged particles onto the substrate under vacuum. In other cases where the write beam is a radiation beam, *e.g.*, x-ray, UV, or visible radiation, the beam focusing assembly includes corresponding optics for focusing and directing the radiation to the substrate.

It is understood that while the invention has been described in conjunction with the detailed description thereof, the foregoing description is intended to illustrate and not limit the scope of the invention, which is defined by the scope of the appended claims.